ADA

DEVELOPMENT OF A TEST RIG FOR MEASURING ISENTROPIC BULK MODULUS

INTERIM REPORT
TFLRF No. 438

by
Scott A. Hutzler

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Eric R. Sattler, Patsy A. Muzzell & Nick C. Johnson

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD0004 – Task XXIII)

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Gary Bessee

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14. ABSTRACT

Bulk modulus is a measure a fluid's compressibility. In fuel systems, the bulk modulus of the fuel can have a significant impact on fuel behavior and performance in engines by affecting injection timing. While the behavior of most petroleum-derived fuels are well-understood, the emergence of new bio-based and synthetic fuels have demonstrated some properties that are beyond current experience. Therefore, as part of a complete fit-for-purpose analysis, the need for a bulk modulus test rig was identified. The objective of this effort was to design and build a test rig for measuring isentropic bulk modulus at pressures and temperatures up to 30,000 psi and 100°C, respectively. To-date, the measurement of high pressure/temperature speed-of-sound on several fluids has been successfully demonstrated. Plans are underway to incorporate a high pressure/temperature densitometer to improve the bulk modulus accuracy.

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EXECUTIVE SUMMARY

Bulk modulus is a measure of a fluid's compressibility. Contrary to popular notions, all fluids do exhibit some degree of compressibility. In fuel systems, the bulk modulus of the fuel can have a significant impact on fuel behavior and performance in engines by affecting injection timing. The trend toward the use of higher pressure, such as in High Pressure Common Rail (HPCR) fuel systems, demonstrates the need to better understand how the compressibility of fuels are affected at elevated pressures. While the behavior of most petroleum-derived fuels are well-understood, the emergence of new bio-based and synthetic fuels have demonstrated some properties that are beyond current experience. Therefore, as part of a complete fit-for-purpose analysis, the need for a bulk modulus test rig was identified.

The objective of this effort was to design and build a test rig for measuring isentropic bulk modulus of hydrocarbon-based fluids - primarily aviation and diesel fuel. The goal was to create a test rig that can measure the speed-of-sound in fluids at pressures and temperatures up to 30,000 psi and 100°C, respectively.

The measurement of isentropic bulk modulus requires accurate measurement of speed-of-sound and density at a selected pressure and temperature. To-date, the measurement of high pressure/temperature speed-of-sound on several fluids has been successfully demonstrated. In the conduct of this research it was determined that an improved method for density would be needed to achieve the accuracy desired for bulk modulus. Therefore, plans are underway to incorporate a high pressure/temperature densitometer to be tentatively completed by the end of January 2013.

FOREWORD/ACKNOWLEDGMENTS

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ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Lab
HPCR	High Pressure Common Rail
SwRI	Southwest Research Institute
WPAFB	Wright Patterson Air Force Base

1.0 BACKGROUND

Bulk modulus is a property that indicates the compressibility of a fluid. Bulk modulus has an inverse relationship with compressibility. Contrary to popular notions, all fluids do exhibit some degree of compressibility. In systems that require a fast response to an applied load, such as hydraulically actuated systems, a highly compressible fluid can lead to a delayed response. In fuel systems, the bulk modulus of the fuel can have a significant impact on fuel behavior and performance in engines by affecting injection timing due to higher pressures. The trend toward the use of higher pressure, such as in High Pressure Common Rail (HPCR) fuel systems, demonstrates the need to better understand how the compressibility of fuels are affected at pressures approaching 30,000 psi.

While the behavior of most petroleum-derived fuels are well-understood, the emergence of new bio-based and synthetic fuels created cause for concern. While still hydrocarbon-based, the varying chemical composition of these alternative fuels have been shown to create a range of compressibilities. Therefore, as part of a complete fit-for-purpose analysis, the need for a bulk modulus test rig was identified. Two general approaches exist for determining the bulk modulus of compressibility for fluids: the isothermal method and the isentropic method.

The isothermal method is based on classical pressure-volume-temperature measurements. ASTM D6793 defines a method and apparatus for determining the isothermal bulk modulus. Isentropic bulk modulus is typically calculated from speed-of-sound measurements. When a fluid is compressed it's temperature rises. As the temperature rises, the fluid tries to expand causing an additional increase in pressure. When compression occurs slowly, as in the isothermal method, the generated heat is allowed to dissipate reducing the effect of thermal expansion. Rapid compression, as in the isentropic method, results in a pressure measurement due to compression and thermal expansion. Most hydraulic applications are considered isentropic due to the rapid movement of tightly controlled systems. Therefore, the isentropic method is often the preferred technique.

Isentropic methodology is based on the relationship $\beta = c^2 \, x \, \rho$, where β is the isentropic bulk modulus, c is the speed-of-sound in the fluid, and ρ is the density all measured under a given set of pressure and temperature conditions.

2.0 OBJECTIVE

The objective of this effort was to design and build a test rig for measuring isentropic bulk modulus of hydrocarbon-based fluids - primarily aviation and diesel fuel. The goal was to create a test rig that can measure the speed-of-sound in fluids at pressures and temperatures up to 30,000 psi and 100°C, respectively.

The objective of this report is to document the status of the test rig to date and provide an update on the pending modifications to the rig based on our initial findings. Several aspects of the operation of this apparatus will change once the modifications to the system are complete. All of the planned modifications are designed to make the system more accurate and more user-friendly. A detailed operating manual will be developed once the system is reassembled.

3.0 APPROACH

Prior to undertaking the build-up of the full-scale, high-pressure model, a small, benchtop prototype system was built to confirm our ability to accurately measure speed-of-sound. Although only able to operate at atmospheric pressure and temperatures up to 50°C, the prototype system was found to provide highly accurate speed-of-sound data and was used to build an initial database of comparative isentropic bulk modulus data on a wide range of fuels (see Section 7.1). Once this was accomplished successfully, we moved on to construct the full-scale system. Both systems are able to make use of the same basic instrumentation.

4.0 TEST FLUIDS

A variety of petroleum-based and alternative fuels were used in this effort. All of the alternative aviation fuels and their blends were provided by AFRL (WPAFB). The petroleum-based fuels and biodiesels were on-hand at SwRI.

5.0 APPARATUS

5.1 INSTRUMENTATION

The instrumentation required to create and measure the acoustic signals is common to both the prototype and high-pressure apparatus. A pulser/receiver unit (Olympus 5072-PR) is used to drive the ultrasonic transducer and the signals generated are measured using a digital oscilloscope (LeCroy WaveSurfer 24MXs-A). The oscilloscope is used to measure the time-of-flight of the acoustic signals as they reflect off internal surfaces and return to the transducer. The prototype system uses a single-element immersion transducer (Olympus V326-SU, 5MHz) that is capable of direct contact with the fuel but limited to approximately 50°C maximum temperature. The high-pressure system uses a dual element transducer (Olympus 791-RM, 5MHz) which is able to tolerate temperatures exceeding 100°C. Experiments were also conducted with an Olympus DHC706-RM (dual element, 2.25 MHz) transducer and found to give better signal quality. This will likely be the choice of transducer for subsequent designs.

5.2 PROTOTYPE APPARATUS

The prototype system, shown in Figure 1, consists of an ultrasonic immersion transducer wedged between two plates. The lower plate acts as a platform to support the apparatus on top of a beaker filled with the test fluid. The cruciform design of the mounting bolts allows the transducer angle to be adjusted in small increments to improve the signal strength and remove echoes caused by reflections from the walls. The cylinder below the plates includes a highly-polished reflector plate as the target for the ultrasonic pulse. A small hole through the plates allows a thermocouple to be inserted to measure the fluid temperature.

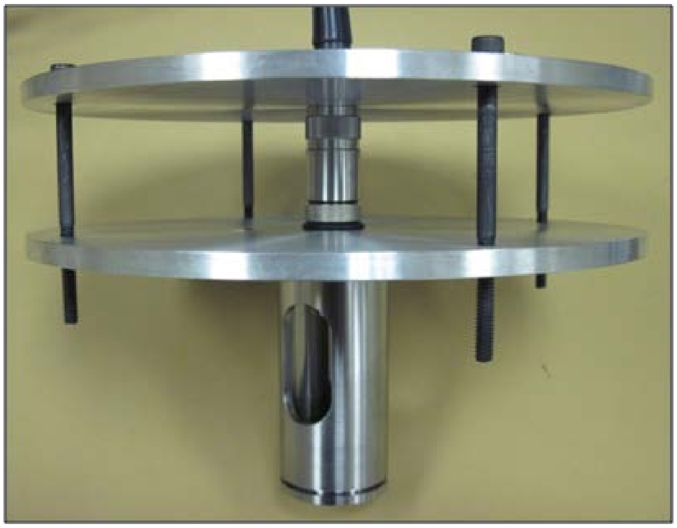

Figure 1. Prototype Speed-of-Sound System

5.3 HIGH-PRESSURE APPARATUS

The high-pressure bulk modulus apparatus in its original configuration (Figure 2) consists of the high-pressure components (Figure 3) housed in a high-temperature oven. The high pressure components consist of the custom high-pressure cell (Figure 3, lower left), a high-pressure generator (Figure 3, lower right), a pressure transducer (Figure 3, center left), and inlet/outlet valves. Other peripheral equipment (not shown) are a peristaltic pump to transfer fuel in and out of the system, fluid containers for test fuel and flushing solvents, and a dry air cylinder for drying the system (and later for calibrating the densitometer).

Figure 2. Bulk Modulus Apparatus

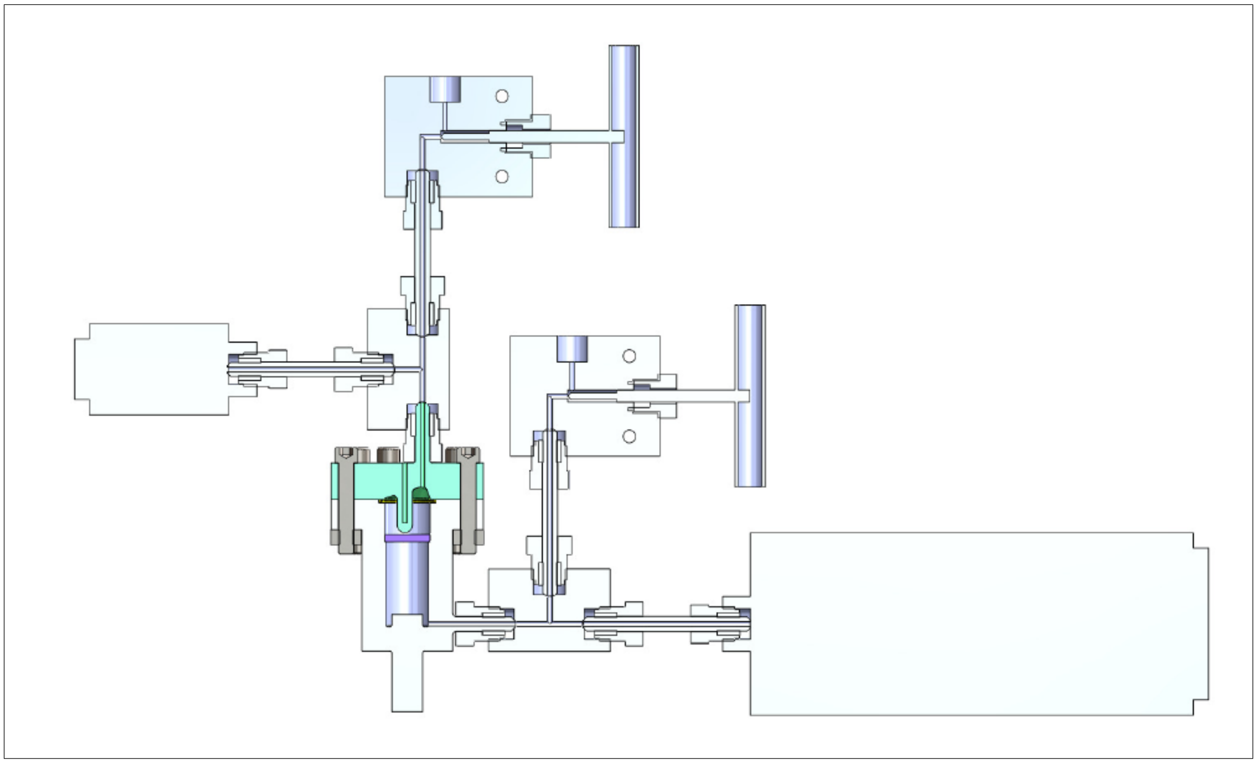

Figure 3. High-Pressure Plumbing

The custom, high-pressure cell, shown in Figure 4, was fabricated from 17-4PH heat-treated steel. The cell is a three-part design consisting of a top and bottom with a thermowell sandwiched in between. The top interior is conical shaped to prevent entrapment of air. All of the mating surfaces within the cell received a reflective finish in the 4-8 µm range. An 8 µm finish is expected to provide an adequate seal for gases like helium or hydrogen. After some experimentation, typical Viton O-rings were chosen to create the internal seal. The design of the O-ring groove combined with the parallelism and highly polished finish of the mating surfaces is expected to limit the extrusion of the O-ring even at high pressures. The high-pressure cell is rated for 30,000 psi, the pressure transducer 50,000 psi, and the remainder of the plumbing 60,000 psi.

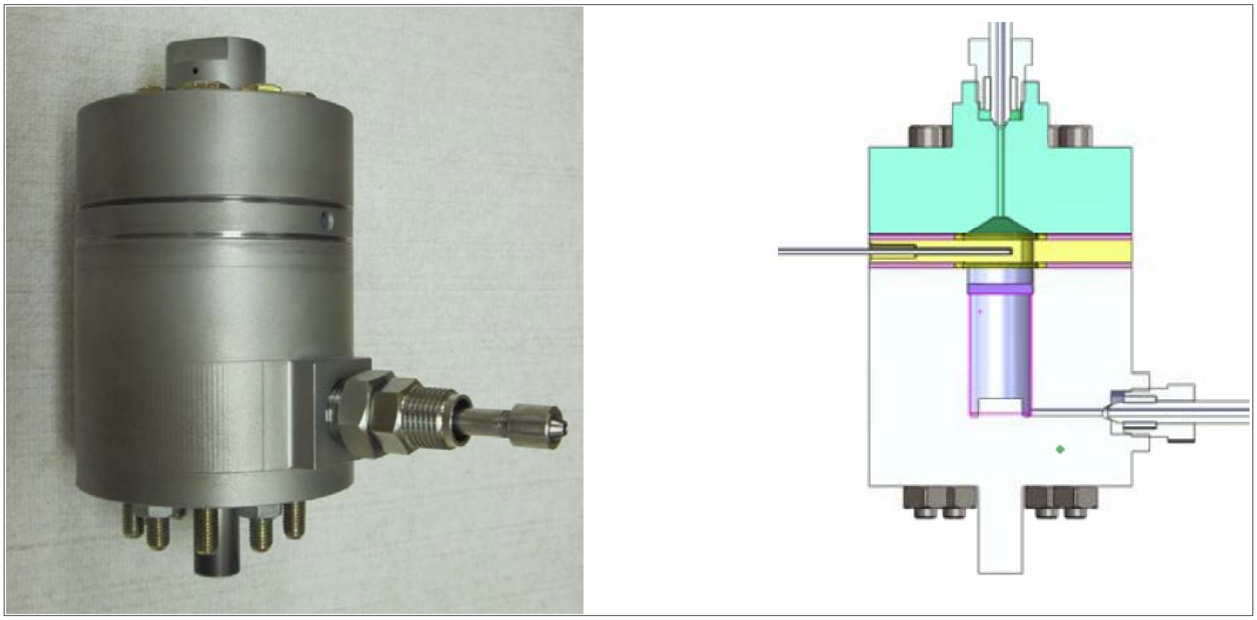

Figure 4. High-Pressure Cell

6.0 MEASUREMENTS AND CALCULATIONS

6.1 PROTOTYPE APPARATUS

The prototype apparatus is calibrated using reagent grade water. This calibration is done periodically and especially if disassembled for cleaning. Using the temperature-dependent speed-of-sound in water, the distance from the transducer to the reflector plate is calculated as:

d=ct/2, where

d =distance, m

c =speed-of-sound, m/s

t = time-of-flight, seconds

The result is halved because the time-of-flight includes the round-trip distance for the acoustic signal. The distance to the reflector plate was found to be nominally 42 mm. This result was used in subsequent measurements as the distance, d, in c=2d/t when determining the speed-of-sound for unknowns. Alternatively, if one knew the exact distance based on the fabrication of the device then that could also be used.

6.2 HIGH-PRESSURE APPARATUS

Measurement of the speed-of-sound on the high pressure apparatus is slightly more involved. In this case, since the acoustic signal is passing through the cell well and back it is necessary to isolate the reflections from the inner wall (called the stationary echo) and the reflector (called the target echo). The stationary echo is the point at which the signal enters the fluid from the cell wall. This signal should remain relatively stationary across the range of temperatures expected. The second echo, the target echo, is the point at which the signal reflects off the internal target after having passed through the fluid. Using these times and the known physical dimensions of the cell, the speed-of-sound of the fluid is calculated as:

$c=2d/(t_r - t_s)$, where

d= pathlength of the cell, m

t_r=time-of-flight of the target echo, s

t_s= time-of-flight of the stationary echo. s

This effectively isolates the speed of the acoustic signal in the fluid only.

7.0 RESULTS AND DISCUSSIONS

7.1 PROTOTYPE APPARATUS

7.1.1 Speed-of-Sound Verification

Based on the measurement techniques discussed above, cyclohexane, having a known speed-of-sound of 1228.7 m/s at 30°C [1], was used routinely as a verification sample throughout the testing of fuels. The cyclohexane results shown in Table 1 were found to have a standard deviation of just 0.54 m/s and a relative error of ≤0.06%. A nominal test temperature of 30°C was adopted as the lowest temperature that could be reliably maintained in our ovens.

7.1.2 Preliminary Bulk Modulus Data

The prototype apparatus was used to measure the isentropic bulk modulus of a variety of fuels (see Table 1). These results clearly show the distinct differences in compressibility among a range of fuel types. These results show that the bulk modulus is largely (but not always) dependent on the density of the fuel. The data also shows that the alternative aviation fuels typically have a much lower speed-of-sound than do their petroleum-based counterparts. The diesel and biodiesel samples are also significantly higher than the aviation fuels. Although not discernible from this data, the speed-of-sound for blends of petroleum and synthetic fuel generally lie proportionally between the values for the neat fuels. The density values were obtained by ASTM D4052.

Table 1. Isentropic Bulk Modulus Data for Select Fuels

Description	Speed-of-Sound @ 30°C m/s	Density @ 30°C g/cm^3	Isentropic Bulk Modulus @ 30°C psi
B100 Soy	1377	0.8745	240,483
B50 Blend	1350	0.8517	225,279
B20 Blend	1336	0.8385	217,073
Premium Ultra-Low Sulfur Diesel	1329	0.8241	210,966
JP-8	1284	0.8016	191,712
Jet A	1262	0.7873	181,872
50/50 Tallow HRJ /JP-8	1258	0.7697	176,642
50/50 Camelina HRJ /JP-8	1247	0.7661	172,710
TS-1	1256	0.7497	171,479
GEVO ATJ / JP-8	1231	0.7701	169,372
Tallow HRJ	1241	0.7463	166,620
Sasol IPK	1212	0.7497	159,690
Camelina HRJ	1220	0.7391	159,600
Shell FT-SPK	1205	0.7247	152,657
GEVO ATJ	1181	0.7455	150,769
cyclohexane (check sample)	1228.43 (lit 1228.72)	--	--
cyclohexane (check sample)	1229.38 (lit 1228.72)	--	--
cyclohexane (check sample)	1228.47 (lit 1228.72)	--	--
cyclohexane (check sample)	1228.44 (lit 1228.72)	--	--

7.1.3 Low-Temperature Speed-of-Sound Data

Although not applicable to the high-pressure system, we demonstrated the use of the prototype system at sub-ambient temperatures as well (see Figure 5). This simply shows that such a technique could be used across a wide temperature range given the means to control the temperature. In this demonstration, we compared a JP-8 sample to a 50/50 blend of that fuel with an ATJ fuel. The expected trends were observed – the speed-of-sound decreased with an increase in temperature and the blend gave a lower value than the neat fuel.

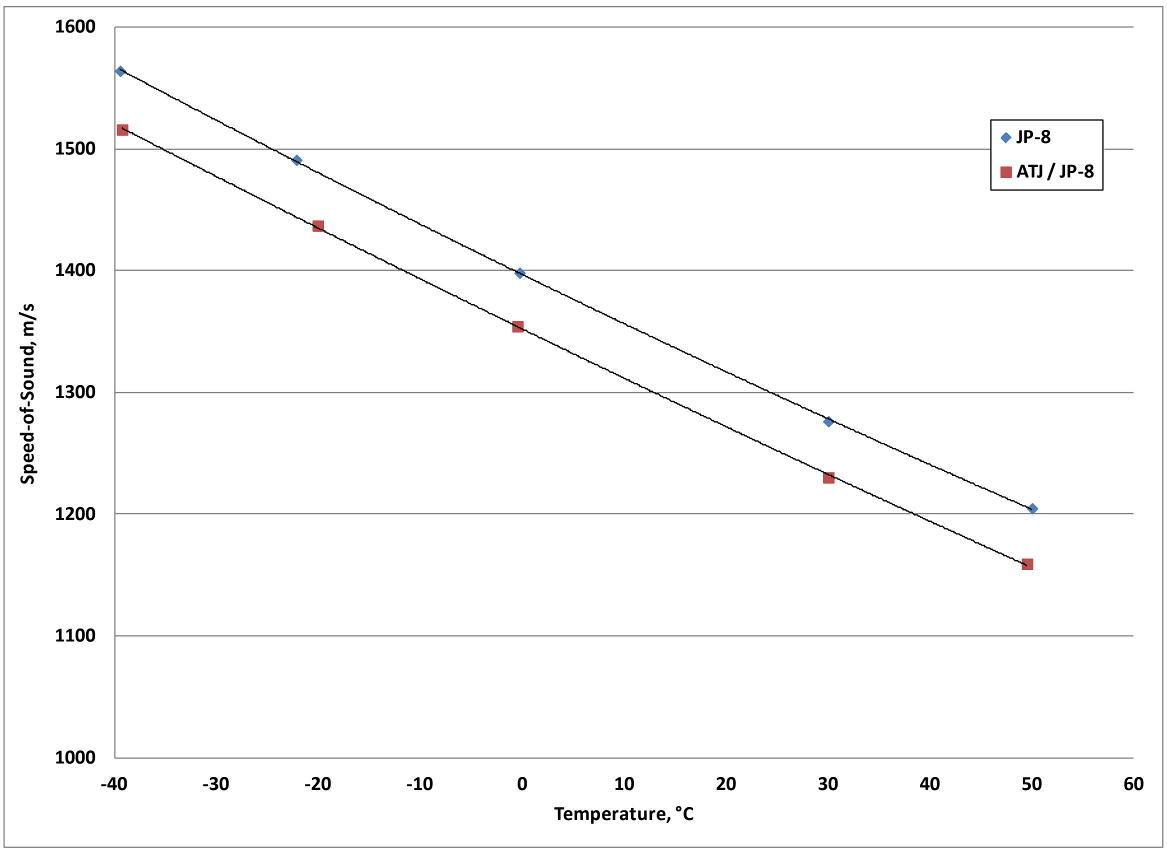

Figure 5. Low Temperature Speed-of-Sound

7.2 HIGH PRESSURE APPARATUS

7.2.1 Speed-of-Sound Verification

In our first attempts at this technique, we used the known speed-of-sound of water, the known distance to the target (1.2”), and an approximate value for the speed-of-sound in the metal to isolate what was believed to be the first stationary echo. Combined with the target echo, this gave a speed-of-sound for water of 1511.6 m/s (literature 1509.5 @ 30°C, 0.14% error). We then performed the same measurement on cyclohexane with a result of 1230.6 m/s (literature 1228.7 @ 30°C, 0.15% error).

Since little data exists for speed-of-sound and/or bulk modulus of fuel, we chose to verify the system further using fluids that are well-documented. The speed-of-sound of water can be found throughout the literature. We found an interactive site [2] based on a literature reference [3] useful for tabulating water speed-of-sound data as a function of pressure and temperature. To confirm the operation of the apparatus on a hydrocarbon fluid, we chose heptane as it is also well-documented in the literature [4].

7.2.2 Water

The speed-of-sound data for water as a function of pressure and temperature is shown in Figure 6. This data shows a good correlation to literature data. This figure also highlights an unusual characteristic that’s unique to water. As the temperature of water decreases, its density actually *decreases* (the familiar expansion of frozen water) causing the speed-of-sound to decrease as well. Most other fluids show the opposite effect as their density actually increases with decreasing temperature. This can be observed in the heptane data below.

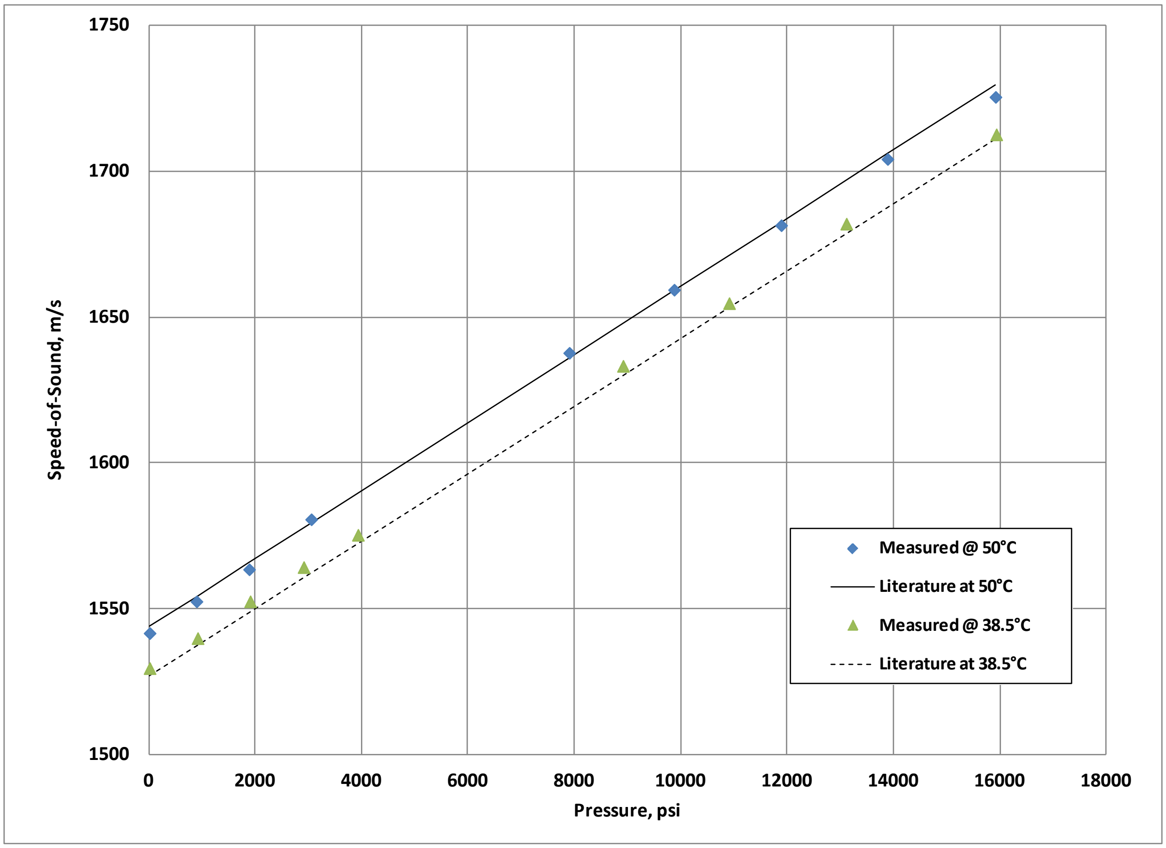

Figure 6. Speed-of-Sound Verification - Water

7.2.3 Heptane

The speed-of-sound of heptane was measured across a range of temperatures and pressures and found to give a good correlation to literature data. This data shows the expected trend for hydrocarbons with an increase in the speed-of-sound as temperature decreases. Note that the measured value at 23.9°C is compared to a literature value of 25°C. Even at that slight temperature difference the bias is observable and directionally correct.

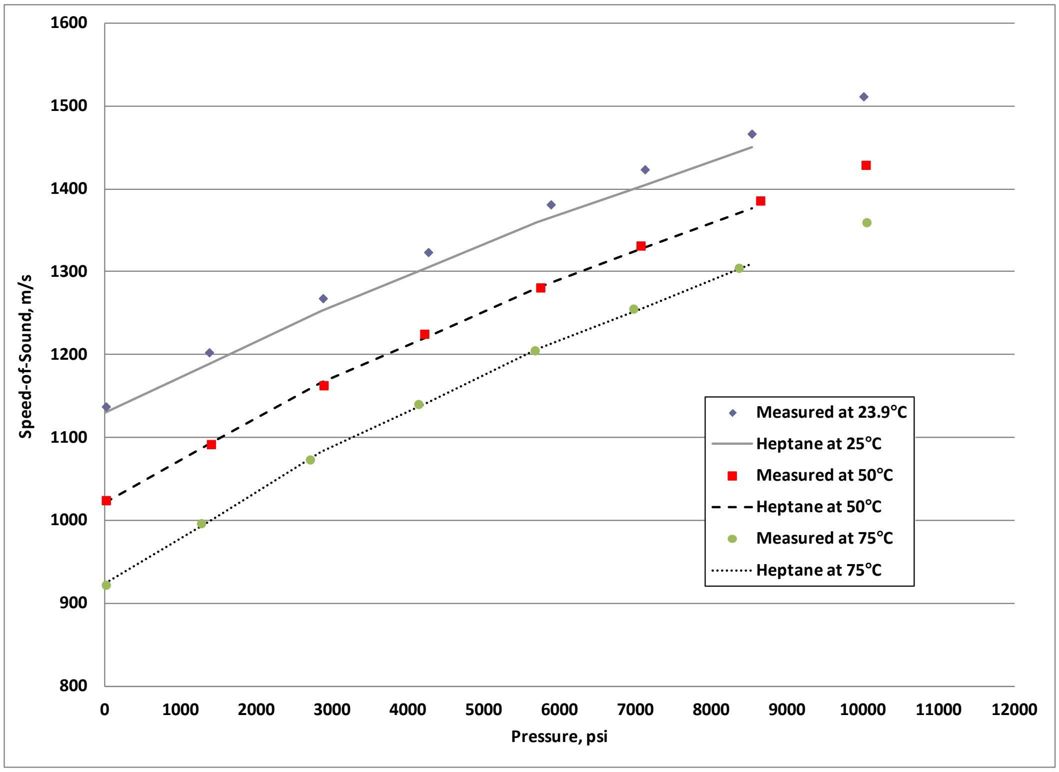

Figure 7. Speed-of-Sound Verification - Heptane

7.3 ISSUES MEASURING DENSITY

The determination of isentropic bulk modulus requires the speed-of-sound and density to be known accurately at a given temperature and pressure. Based on the findings above, we believe that an accurate speed-of-sound measurement can be obtained across a wide range of temperatures and pressures. For density, the originally conceived approach was to track the volume change in the system using a shaft encoder on the high-pressure generator and then back-calculate the change in density assuming a linear relationship. Unfortunately, after some experimentation with the hardware we concluded that this was not an optimal approach. Variables such as entrapped air, system expansion, and slop in the generator would defeat any hope of an accurate density measurement. The clear solution was to incorporate a high pressure/temperature densitometer. Coupled with the highly accurate and precise speed-of-sound data, this would give the most accurate bulk modulus data. Coincidentally, TARDEC had recently offered to supply an Anton-Paar densitometer capable of 20,000 psi and 200°C. It seemed logical that we couple this densitometer to the current system.

8.0 PENDING MODIFICATIONS

The latest schematic for the bulk modulus apparatus is shown in Figure 8. Since the densitometer is only rated for 20,000 psi, it was necessary to place the high-pressure cell and the densitometer in separate legs. Should experiments be performed below 20,000 psi then density and speed-of-sound measurements can be conducted simultaneously. For measurements above 20,000 psi, speed-of-sound measurements can be collected as usual while the density will need to be extrapolated from pressure/temperature curves below 20,000 psi. The high-pressure cell will be modified slightly to remove any sharp edges from the acoustic path (Figure 9). A special holder is also being fabricated (Figure 8, blue, bottom right) to help hold and align the ultrasonic transducer.

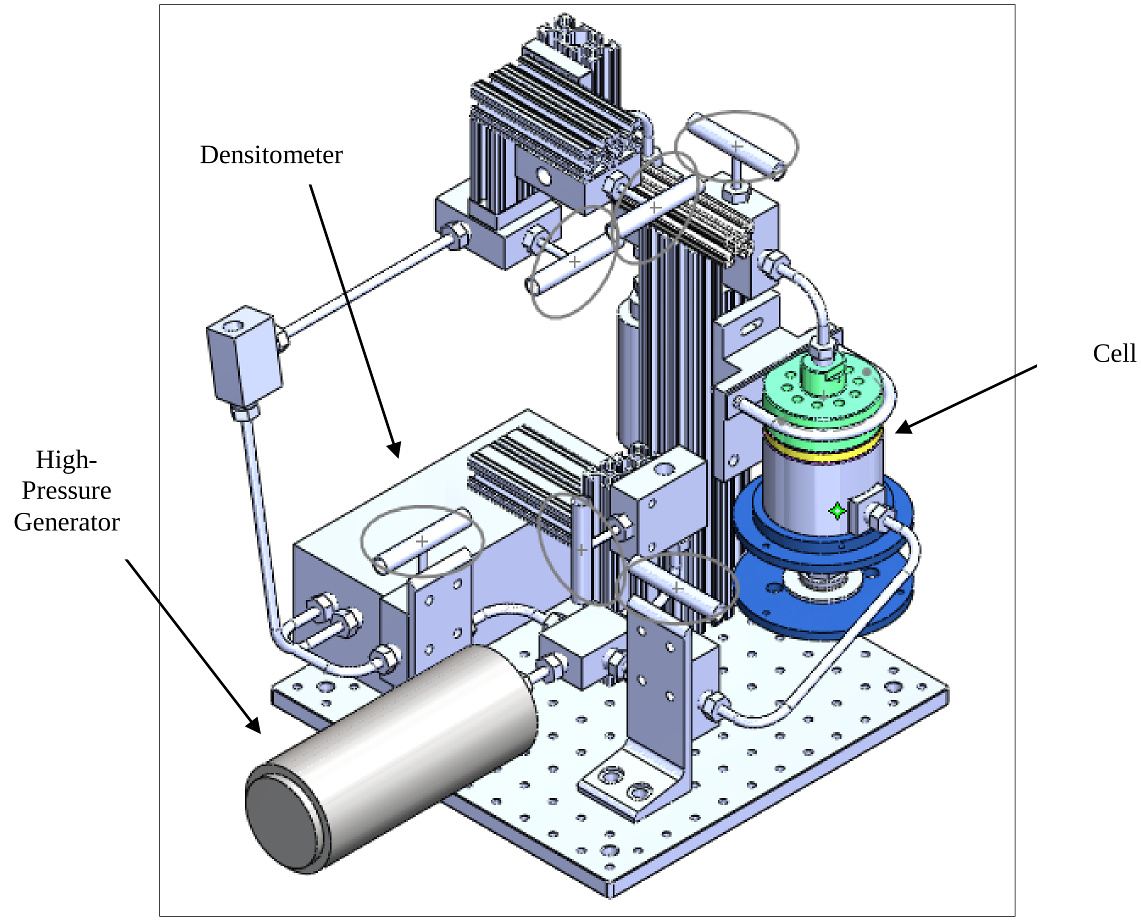

Figure 8. Revised Plumbing Schematic

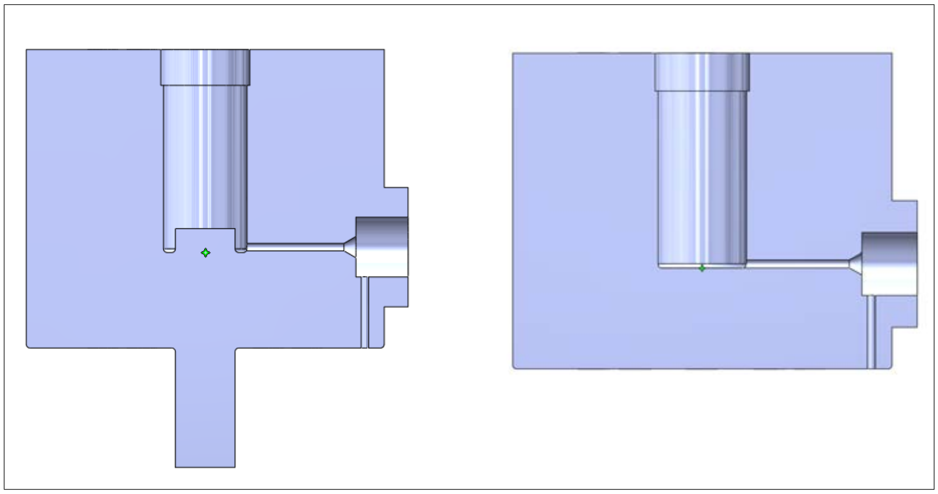

Figure 9. High-Pressure Cell Modifications - Before (left) and After (right)

9.0 CONCLUSIONS

Using a custom-built test rig, speed-of-sound measurements at high temperature and pressure have been demonstrated successfully and verified against several known fluids and applied to real-world fuel samples. Using this approach, a preliminary database of bulk modulus data (atmospheric pressure) was assembled for a wide range of petroleum and synthetic fuels. The test rig developed under this effort will serve as a good template for future builds. Based on this research, it was determined that a different approach to measuring density at high temperature/pressure would be needed to enhance the accuracy of the bulk modulus data under those conditions.

As of this writing, the high-pressure bulk modulus apparatus is undergoing modifications to incorporate a high pressure/temperature densitometer. This new design will be the prototype for the next four units being built under WD 0019 and WD 0021. The modifications to the current rig are expected to be complete by the end of January 2013 with verification experiments to begin immediately after. Since this unit has been used as a testbed and undergone several modifications, it was decided that this unit would remain at SwRI and one of the new units would be provided to TARDEC. This would ensure that all fielded units are as identical as possible.

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